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Visual Perception of Non-rectangular Flashes at Supra-threshold

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Executive Summary

This latest visual experiment, in a series of experiments carried out by the General Lighthouse Authorities' Research and Radionavigation Directorate (R&RNAV), studied the conspicuity of non-rectangular flashes of light at observer illuminance levels above the threshold of perception (supra-threshold). A single experienced observer matched the brightness of flashes to a steady light at 0.2 microlux, the illuminance level from which the night time luminous range of a marine aid to navigation light is calculated. Six different flash profiles were observed: rectangle (control); rectangle with 100Hz pulse-width modulation; asymmetrical triangle with a rising edge; asymmetrical triangle with a falling edge; symmetrical triangle; and Gaussian. The durations of these flashes varied from 0.025 seconds to one second. The aim of the experiment was to ascertain how different flash shapes and durations affect conspicuity and to ascertain the best method of modelling the conspicuity of a marine aid to navigation light.

Results showed that several existing methods of effective intensity evaluation gave significant errors when applied to the flash profiles observed, including the IALA recommended Modified Allard Method (MAM). However, When the visual impulse response function in the current MAM model was modified by using a mathematical 'shear transformation', a better fit to the observed data was obtained. As with other studies at this supra-threshold level, a visual time constant of 0.1 seconds was found to give a better fit to data than the 0.2 seconds used at threshold levels. Since the term 'effective intensity' is only valid at the threshold of perception, the term 'apparent intensity' is used in this document to quantify supra-threshold conspicuity.

Recommendations include using the Modified Allard Method with a 'shear q3' visual impulse function and a visual time constant of 0.1 seconds for the determination of apparent intensity of marine aid to navigation lights at 0.2 microlux illuminance. Presentation of the results of this experiment to IALA and CIE is also recommended, along with a request to review the term 'Modified Allard Method'.

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1 Introduction

A recent experiment by the Research and Radionavigation Directorate (R&RNAV) studied the conspicuity of flashes with a non-rectangular profile at the threshold of perception**Error! Reference source not found.**. This similar experiment studied the conspicuity of non-rectangular flashes at an illuminance above the threshold of perception (supra-threshold). Marine aids to navigation exhibit flashing lights with many different rhythmic characters, consisting of repeated flashes of varying duration and shape. Although much is known about the conspicuity of flashes with rectangular flash profiles, less is known about flashes with non-rectangular flash profiles, especially at levels above the threshold of perception.

The experiment involved a single observer (observer I), of known consistency and performance, carrying out observations of a series of flashing lights in complete darkness and matching the brightness of the flash with that of a steady light at an illuminance of 0.2 microlux. This level of illuminance is significant because it is the internationally agreed level upon which the night time luminous range of marine aid to navigation lights is based; a supra-threshold level, considered bright enough to enable the colour and rhythmic character of a flashing signal light to be reliably identified. Brightness matching experiments had previously been carried out by R&RNAV [RD13] [RD14], based on a method used by Toulmin-Smith and Green in 1933 [RD19].

Flash profiles observed were: rectangle; rectangle with 100Hz pulse-width modulation (PWM); asymmetrical triangle with rising edge (up triangle); asymmetrical triangle with falling edge (down triangle); symmetrical triangle; and Gaussian. Flashes all had the same peak intensity; flash durations varied between 0.025 seconds and one second.

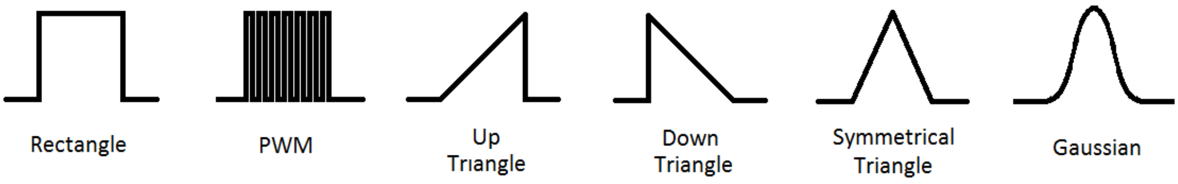


Figure 1 Flash Profiles used in the Experiment

The observer was experienced and had previously been used in visual experiments for R&RNAV in the same location, the dark room in the R&RNAV Lights Laboratory at Harwich, UK [RD13] [RD14] [RD15] [RD20].

2 Terminology

2.1 apparent intensity, I_a

When a light is exhibited rhythmically, the full actual intensity is not appreciated by the eye. The reduced value is known as the 'apparent intensity' and the reduction factor is a function of the duration of the flash and the illumination at the eye of the observer [RD5]

2.2 effective intensity (of a flashing light), I_{eff}, I_e

luminous intensity of a fixed light, of the same relative spectral distribution as the flashing light, which would have the same luminous range as the flashing light under identical conditions of observation [RD6]

2.3 flashing light

rhythmic light in which every appearance of light (flash) is of the same duration and the total duration of light in a period is clearly shorter than the total duration of darkness

NOTE: The term "eclipse" is used for the interval of darkness between two successive distinct appearances of light. [RD6]

2.4 flash (of light)

brief appearance of light, the intensity of which starts from a negligible amount, increases to a significant level, and falls to a negligible amount [RD6]

2.5 flash duration

period of time in which all the flash waveform necessary for determining the effective intensity of the flash is included[RD6]

2.6 flash profile

characteristic variation of instantaneous luminous intensity over the course of time during an appearance of light (flash)

2.7 fovea

central part of the retina, thin and depressed, which contains almost exclusively cones and forming the site of most distinct vision [RD6] (hence foveal vision)

NOTE: The fovea subtends an angle of about 0.087 radians (5°) in the visual field[RD6]

2.8 impulse response function, *q(t)*

the output signal of a system that results when an impulse is applied to the system input

for the human visual system, it is a hypothetical output signal in the human visual system, as a function of time *t*, in response to an instantaneous visual input stimulus (CIE proposed definition)

2.9 luminous range (CIE)

greatest distance at which a given signal light can be recognised in any particular circumstances, as limited only by the atmospheric transmissivity and by the threshold of illuminance at the eye of the observer [RD6]

NOTE: Typically taken as the distance at which a point source can be detected achromatically

2.10 luminous range (BS 942)

The luminous range of a light depends upon the intensity of the light, the atmospheric transmission, and the illumination required at the eye of the observer, which are related by the following formula:

$$IT^x = Ex^2$$

where:

where:	I	=	intensity of the light
	T	=	atmospheric transmission factor per unit distance
	x	=	distance to the observer
	E	=	illumination at distance x

The accepted value of E for adequate conspicuity after dark is 0.67 sea-mile candelas (or 0.2 microlux).[RD5]

2.11 time-integrated luminous intensity, *J*

time-integral of the (instantaneous) luminous intensity, *I(t)*, over a given duration, *Δt*

NOTE: time-integrated luminous intensity is expressed in candela seconds

2.12 train of flashes

group of two or more flashes, followed by a period of darkness, within a period of a flashing light [RD5]

2.13 visual time constant, *a*

duration related to the human visual processing of a light signal, when a point source is focussed on the fovea at about the threshold of detection[RD16]

NOTE: Although there is no precisely-defined value for the visual time constant, a value of 0.2s is commonly used in effective intensity models for a dark-adapted observer.

3 Scope

The scope of this experiment was the observation of artificially produced point source white lights, flashing and steady, at illuminance levels above the achromatic threshold of human foveal vision. Flash profiles were of duration between 0.025 seconds and one second. The eclipse time between flashes was one second. The flash frequency therefore varied between 0.976Hz and 0.5Hz. Observations were carried out in complete darkness with binocular vision by a dark-adapted observer. All observations were carried out with a reference, or fixation, light to ensure that the observer viewed the point light source in foveal vision.

4 Objectives

The objective of this experiment was to investigate how humans perceived a variety of flash shapes and durations above the threshold of perception in foveal vision at an illuminance level of 0.2 microlux. The results of the visual observations were to be compared with predicted results from the various standard methods of determining effective intensity to assess the suitability of those methods in determining the conspicuity of flashing marine signal lights. Of particular interest was to investigate any differences in perception between asymmetrical triangle flash profiles (up and down triangles).

5 Equipment

Experiments were carried out with equipment used in previous R&RNAV experiments[RD13] but modified to exhibit a variety of different flash shapes. In the Bentham ILFD20QH brightness matching equivalence rig, the 3000K halogen lamp, originally used for the flashing light source, was replaced by a 1W 3000K warm white LED driven by a programmable flash generator specifically built for the purpose. The flashing pattern shutter, originally used to generate rectangular flash profiles by interrupting a steady light, was set permanently open.

5.1 The Modified Bentham ILFD20QH Fixed/Flashing Light Equivalence Rig

The modified Bentham ILFD20QH Fixed/Flashing Light Equivalence Rig comprised a box which contained an integrating sphere with a single 0.63mm diameter pinhole output aperture. One tungsten halogen source and one LED light source input light to the integrating sphere, each via a slit, the width of which could be adjusted to determine the amount of light entering the sphere. The LED light source could be flashed with a number of different profiles and durations controlled by the program in the Programmable Flasher PF1. Shutters controlled which light source, steady or flashing, illuminated the integrating sphere. An internal photometer measured the luminance of the light within the integrating sphere when either shutter was opened. The internal photometer was originally calibrated for a halogen light source but, because of errors in the photometer spectral response, measurement of an LED leads to an error due to differences in the LED spectrum. This error was measured and a spectral correction factor (SCF) of 1.16667 was calculated and applied to LED measured values.

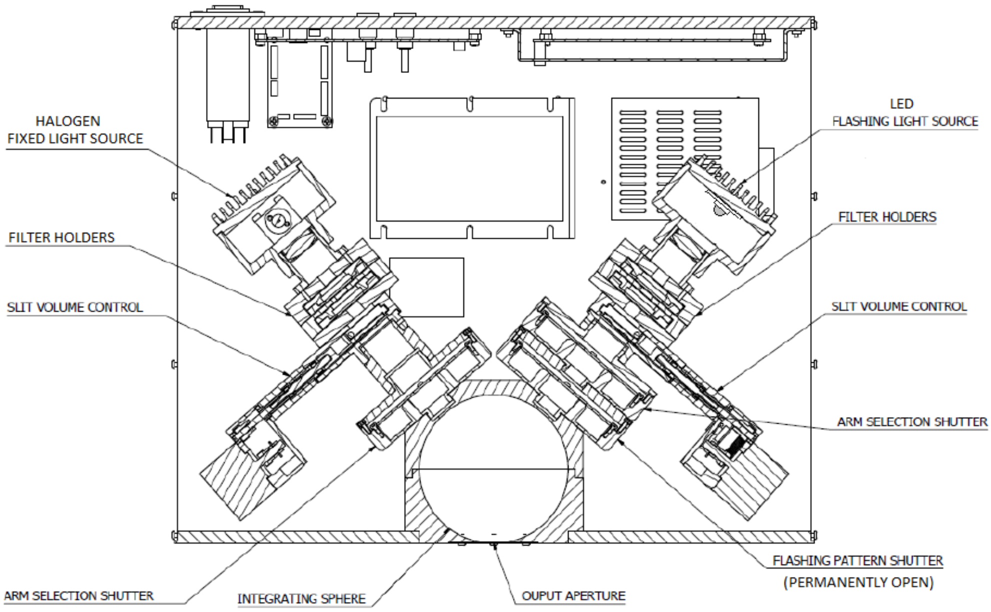


Figure 2 Modified Bentham ILFD20QH Optical Layout

5.2 Bentham ILFD20QH Software

Overall control of the Bentham ILFD20QH was achieved via a USB port connected to a personal computer (PC) with bespoke software installed. The software was used to set up an experiment exhibiting selected flash profiles and rhythms at adjustable levels of illuminance at the eye of the observer. The measured luminance from within the integrating sphere was converted to observer illuminance by the program, using the pinhole area and an observation distance of 2.2 metres.

A game controller was connected to the PC via another USB port; this allowed the observer to toggle between steady and flashing lights as well as to adjust the brightness level of the flashing light. The up/down buttons, used to adjust the brightness of the flashing light, had some random delays built into their operation. Therefore, the observer could not predict the degree of increase or decrease achieved when pressing the up/down buttons.

The brightness of the steady light was preset by the experimenter via the software to 0.2 microlux at the observer.

5.3 Programmable Flasher PF1

The PF1 was a programmable light flasher capable of producing flashes of light of any shape or duration. It was designed for use in visual experiments at relatively low levels of observer illuminance and came pre-programmed with six different flash profiles, each of which had eight or nine flash durations ranging from 25 milliseconds to one second. The pre-programmed flash profiles were rectangular, rectangle with 100Hz pulse-width modulation at 50% duty cycle - 5ms on, 5ms off (PWM), up triangle (leading edge sloping), down triangle (trailing edge sloping), symmetrical triangle (both leading and trailing edges sloping) and Gaussian, any one of which could be selected by a rotary switch. Examples of flash profiles used in this experiment are shown in Annex 2.

The power supply for the PF1 was a 12V 500mA plug-in type with a 2.1mm coaxial DC plug that fitted the DC socket on the PF1; there was no separate on/off switch. The LED provided came with a length of cable fitted with a phono plug allowing connection to the PF1.

Controls

RPUDSG	-	flash profile selector, **R**ectangle, **P**WM, **U**p triangle, **D**own triangle, **S**ymmetrical triangle, **G**aussian
Q/S	-	flash duration order, **Q** = quick flash first, **S** = slow flash first
Reset	-	program reset after selecting flash profile or order
Steady	-	when pressed, brings on a steady light of fixed intensity (when programmed)
Vary	-	controls the intensity of the flash
F/M	-	**F** = repeated (selected) flash with a one second eclipse, when switching to **M** the light continuously displays the peak intensity of the flash depending on the 'Vary' control setting.

Connections

LED	-	LED socket (phono)
USB	-	USB connection (3.5mm stereo jack)
12V	-	12VDC power input (coaxial 2.1mm)

Although designed as a stand-alone device, the PF1 was modified for use with the Bentham ILFD20QH Rig. This involved:

- disabling the 'Vary' control because the intensity was controlled by the observer operating the game controller to vary the slit width within the Bentham Rig;
- ignoring the 'Steady' control because the Bentham ILFD20QH had its own calibrated steady light source;
- ignoring the USB connection, needed to gather measurement results, because the Bentham ILFD20QH measured and stored the results of the experiment.

A 3000K white LED, driven by the PF1 was used to replace one of the tungsten halogen light sources (flashing) in the Bentham Rig.

Figure 3 PF1 Programmable Flasher

5.4 Fixation Light

Although the majority of observations were carried out in complete darkness, a fixation light was used for all observations. The fixation light was designed to ensure that the observer kept the pinhole aperture in foveal vision.

A light source was constructed that consisted of a sheet of 5mm thick clear cast acrylic sheet with a 60mm diameter hole in its centre. One side of the hole was given a slight 45 degree chamfer. At either side of the sheet, the edge was drilled with a 3mm diameter hole into which a 650nm red LED was fitted. The whole of the surface of the sheet was blackened except for the chamfer. The LEDs were wired in series and supplied from a variable current power supply. The sheet was then placed directly in front of the Bentham ILFD20QH such that the pinhole was at the centre of the 60mm hole in the sheet.

When lit, the fixation light formed a thin annular red light, 60mm in diameter, around the pinhole and concentric with it. At the observer distance of 2.2 metres, the subtense angle of the fixation light ring was approximately ±0.8 degrees of arc.

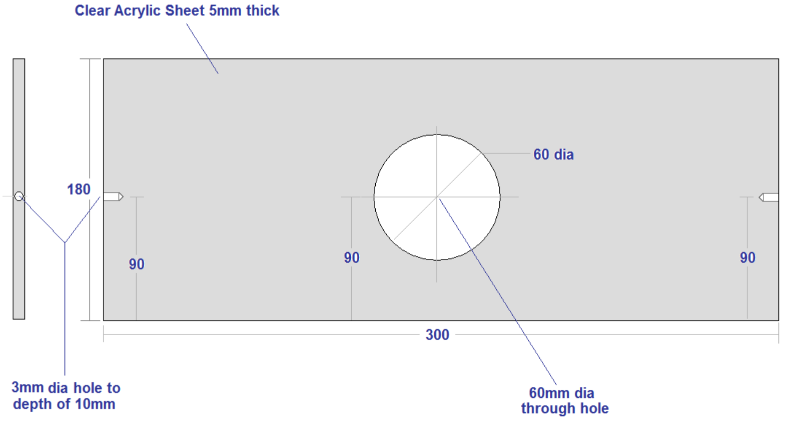


Figure 4 Fixation Light Drawing

6 Experiment Setup

The experiment was set up in a darkened room with the modified Bentham ILFD20QH in one corner and a seat for the observer in the opposite corner. The experimenter was seated alongside the Bentham ILFD20QH, where the PC keyboard and visual display unit (VDU) were installed. The PF1 Programmable Flasher was installed alongside the keyboard.

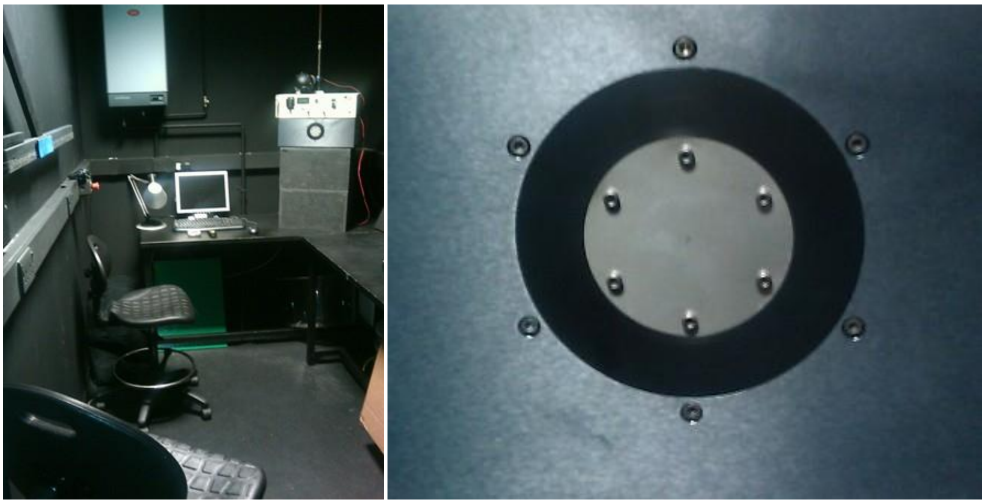


Figure 5 Left: Observer's View of Equipment; Right: Close-up of Pinhole

A hinged bar was installed which could be swung across the dark room and locked into place. The observer could adjust his seating position so that his forehead rested on a padded area on the bar, thereby ensuring his eyes were at the correct height and distance (2.2 metres) from the pinhole.

Figure 6 Left: Observer in Position Right: Experimenter in Position

All light sources within the dark room were disabled and all light from outside was excluded. The VDU was switched off once the experiment was under way.

7 Method

7.1 Experimental Procedure

Preparation

The equipment was switched on and allowed to stabilise for ten minutes. The observer was seated and his position adjusted until he was comfortable and in the correct position with his forehead resting on the padded area of the hinged bar. The programmed experiment was initiated by pressing the 'Run' prompt, after which the VDU screen was switched off. All lights were extinguished and the room checked for stray light.

The observer then waited fifteen minutes to achieve dark adaptation of vision. After a final check for stray light and adopting a comfortable position, the task of visual observation commenced by lighting the fixation light and adjusting its brightness until it could only just be seen. At this level of illuminance, the red annular ring could only be seen in direct vision, not in peripheral vision, which made it difficult to locate in a dark room with no other visual reference.

For this experiment, a method of brightness matching successive steady and flashing lights, for which the Bentham equipment was designed, was used. The observer could toggle between the steady and flashing lights. He could also adjust the brightness of the flashing light. The experimenter controlled the overall experiment and, once observations were under way, advanced to the next flash profile when the observer had confirmed that he was satisfied with the brightness match. A remote mouse was used by the experimenter, who was also in the dark, to avoid using the VDU.

Consecutive Brightness Matching Tests

The observer toggled back and forth between steady and flashing lights, adjusting the brightness of the flashing light until he was satisfied that a brightness match was obtained. He then told the experimenter who switched the PF1 'F/M' switch to 'M' and, using the remote mouse, prompted the Bentham ILFD20QH to measure the absolute photometric peak value of the flashing light which was automatically stored in the program. Occasionally, due to fatigue or lapse of concentration, the observer rested with eyes closed or lowered. When resuming observations, it was sometimes necessary to toggle to the steady light in order to relocate the red fixation light.

At the end of each observation session consisting of eight or nine flashes of varying duration, the flashing character was replaced by a steady light, the illuminance of which could be controlled by the observer. The same method of brightness matching was used to determine the illuminance value of a steady light (steady versus steady).

Recording

At the completion of observations, comments were made where applicable and saved with the results.

7.2 Flashing Light Experiment Profiles

The following flash profiles and durations in seconds were used. The eclipse time between the end of one flash and the start of the next was always one second. The flash duration was the time between the start of the flash and the end of the flash.

Rectangular Forward:	0.025s, 0.05s, 0.1s, 0.2s, 0.3s, 0.4s, 0.5s, 0.7s, 1.0s, steady.
Rectangular Reverse:	1.0s, 0.7s, 0.5s, 0.4s, 0.3s, 0.2s, 0.1s, 0.05s, 0.025s, steady.
PWM Forward:	0.05s, 0.1s, 0.2s, 0.3s, 0.4s, 0.5s, 0.7s, 1.0s, steady.
PWM Reverse:	1.0s, 0.7s, 0.5s, 0.4s, 0.3s, 0.2s, 0.1s, 0.05s, steady.
Up Triangle Forward:	0.05s, 0.1s, 0.2s, 0.3s, 0.4s, 0.5s, 0.7s, 1.0s, steady.
Up Triangle Reverse:	1.0s, 0.7s, 0.5s, 0.4s, 0.3s, 0.2s, 0.1s, 0.05s, steady.
Down Triangle Forward:	0.05s, 0.1s, 0.2s, 0.3s, 0.4s, 0.5s, 0.7s, 1.0s, steady.
Down Triangle Reverse:	1.0s, 0.7s, 0.5s, 0.4s, 0.3s, 0.2s, 0.1s, 0.05s, steady.
Symmetrical Triangle Forward:	0.05s, 0.1s, 0.2s, 0.3s, 0.4s, 0.5s, 0.7s, 1.0s, steady.

Symmetrical Triangle Reverse: 1.0s, 0.7s, 0.5s, 0.4s, 0.3s, 0.2s, 0.1s, 0.05s, steady.

Gaussian Forward: 0.05s, 0.1s, 0.2s, 0.3s, 0.4s, 0.5s, 0.7s, 1.0s, steady.

Gaussian Reverse: 1.0s, 0.7s, 0.5s, 0.4s, 0.3s, 0.2s, 0.1s, 0.05s, steady.

It can be seen therefore, that the observer was required to carry out nine or ten observations per session. The steady light observation always came at the end of a session; its presence informed the observer/experimenter that it was the final observation for that session. The time-integrated intensity of a triangular flash or a pulse-width modulated flash was half that of a rectangular flash of the same duration. The time-integrated intensity of a Gaussian flash was 0.4 of a rectangular flash of the same duration.

8 Results and Discussion

Shown in Annex 1 are the raw results of the brightness matching experiment for the observer. The tables show the values of steady light measured illuminance and flashing light measured peak illuminance for each flash duration of each flash profile. Since the term effective intensity is only valid at the threshold of illuminance, the term apparent intensity has been used throughout this document when referring to levels above threshold (supra-threshold).

8.1 Relative Apparent Intensity, $I_{a\ rel}$

In order to determine the relative apparent intensity, the steady light illuminance value was divided by the flashing light peak illuminance value. A further spectral correction factor of 1.16667 was applied to the LED measured result to account for the spectral matching error of the photometer.

$$I_{a\,rel} = \frac{E_s}{E_0}$$ **Equation 1**

Figure 7 shows the relative apparent intensity plots for the observer for each of the flash profiles observed; error bars show the combined standard errors for flash and steady observations. Further graphs in section 8.2 show comparisons with existing effective intensity models. Annex 3 gives examples of impulse functions used in the convolution methods.

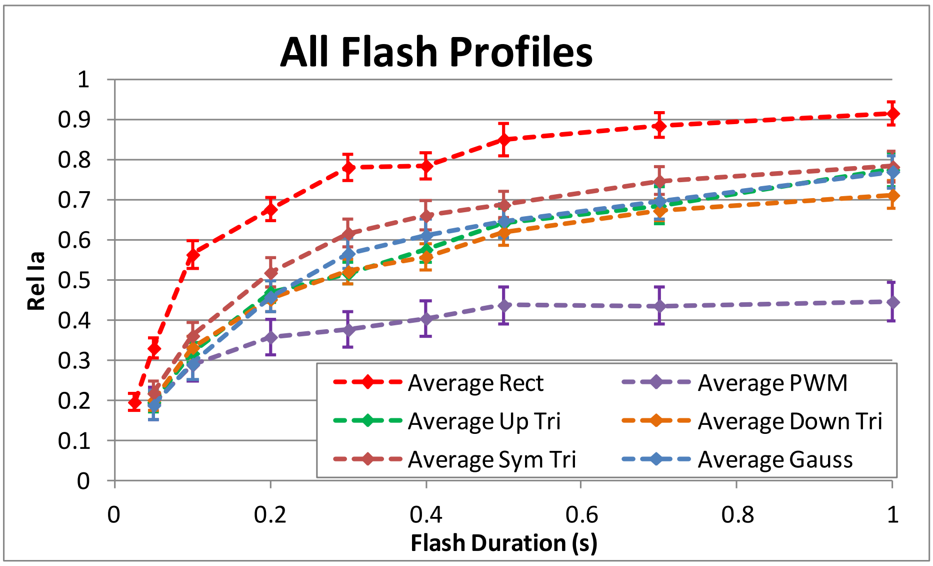


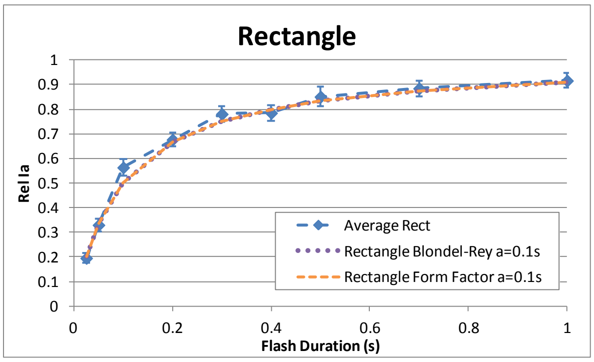
Figure 7 Average Relative Apparent intensity for Observer I

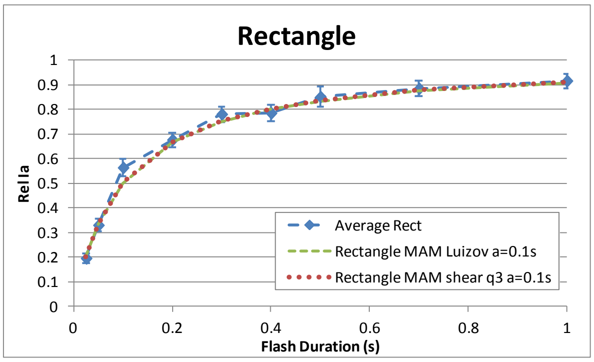
8.2 Comparison of Results to Existing Effective Intensity Models

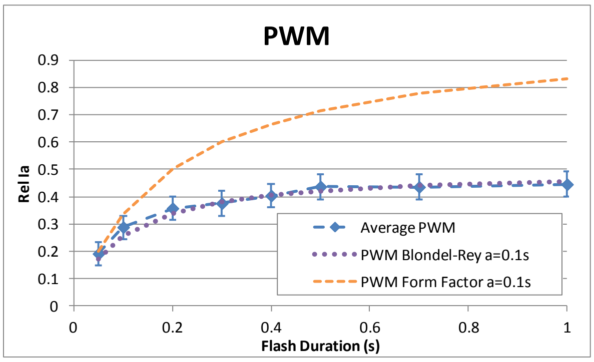
The resultant apparent intensity value, $I_{a\ rel}$, can be compared with expected values from several effective intensity models, namely:

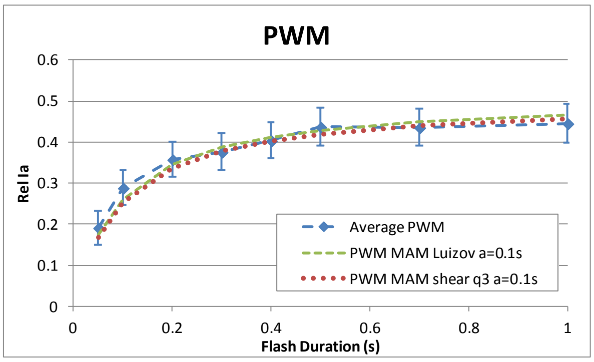
- Blondel-Rey[RD4];
- Schmidt-Clausen Form Factor[RD17];
- Modified Allard Method with impulse response function $q(t) = \frac{a}{(a+t)^2}$ [RD16](MAM Luizov);
- Modified Allard Method with 'shear q3' *q(t)* [RD7] (MAM shear q3).

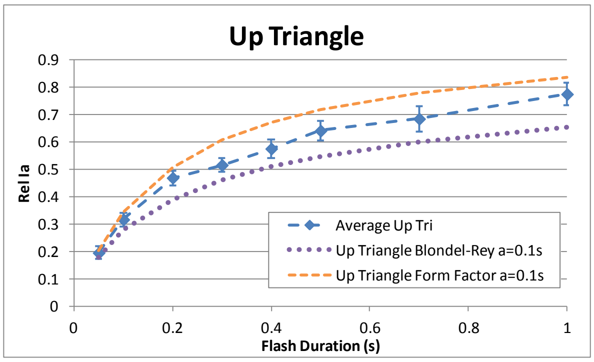
  Up to five different shear functions (q1 to q5) on the original MAM *q(t)* were developed by Dennis Couzin**Error! Reference source not found.**. A visual time constant, *a*, of 0.1 seconds was used for all apparent intensity models, as this was the value recommended in a previous study of rectangular flash profiles at 0.2 microlux illuminance[RD13]. The graphs below show comparisons of the observed apparent intensity results for each flash profile compared with the Blondel-Rey and Schmidt-Clausen Form Factor methods on one graph, and with MAM Luizov and MAM shear q3 methods on the adjacent graph.

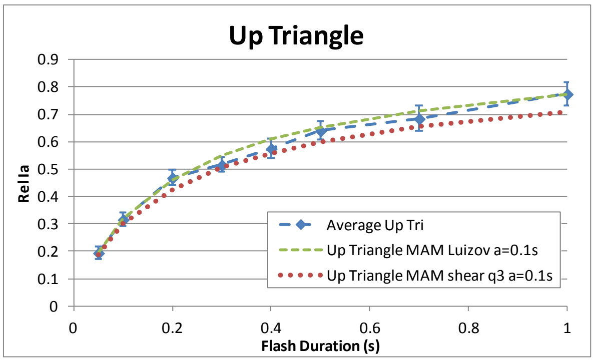












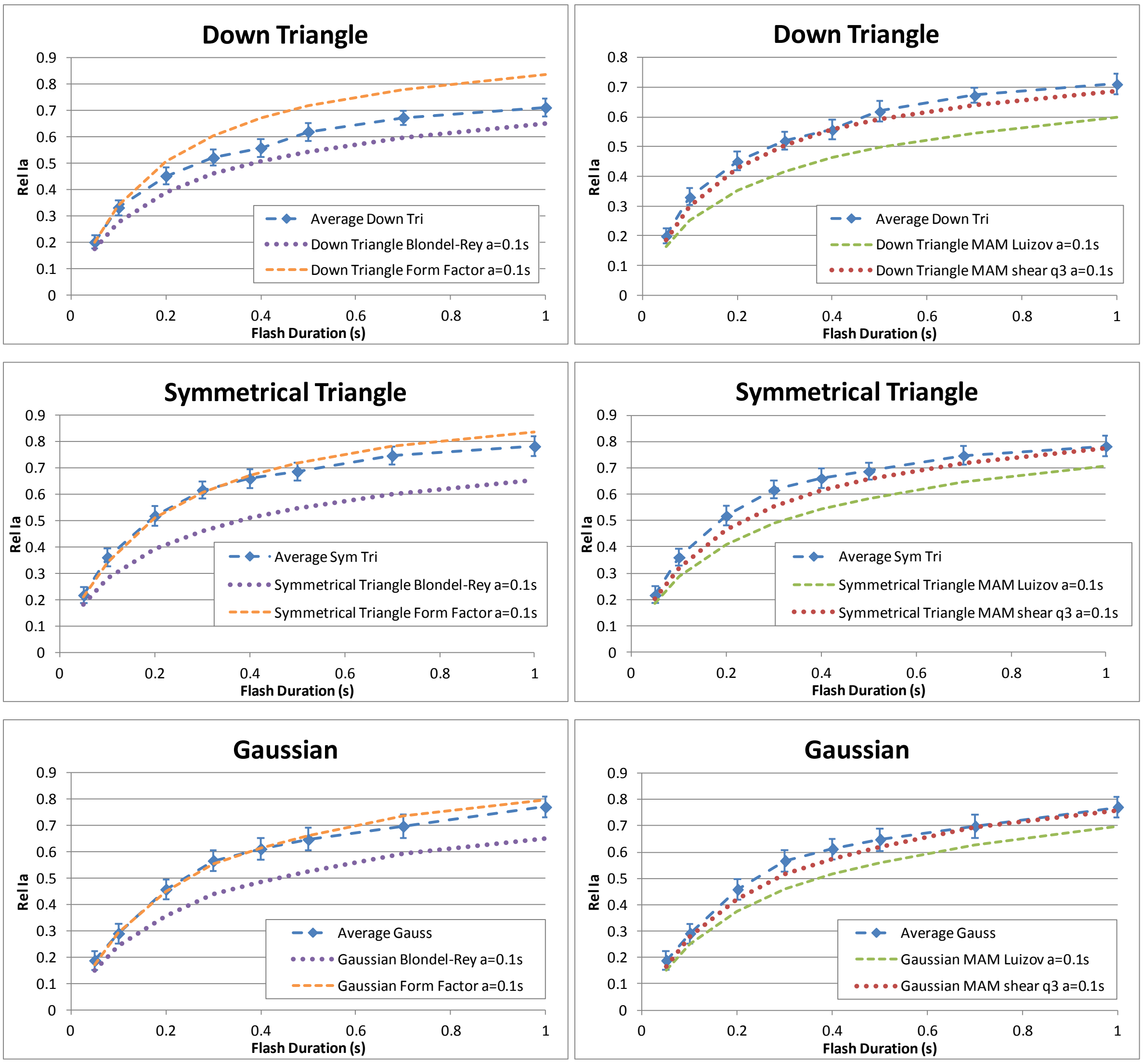


Figure 8 Graphs of Apparent Intensity versus Flash Duration for All Flash Profiles compared with Blondel-Rey, Form Factor, MAM Luizov and MAM shear q3 Methods.

8.3 Discussion

Rectangular flash profiles were observed as a control because many experiments have been carried out with rectangular flashes and all effective intensity models, with the exception of Allard (not considered in this report), agree for this flash profile. The observer's average relative apparent intensity results for rectangular flashes showed close agreement with Blondel-Rey, Form Factor, MAM Luizov and MAM shear q3 methods.

For pulse-width modulated flash profiles: MAM Luizov and MAM shear q3 showed good agreement; Blondel-Rey, if applied using Douglas's formula[RD10], showed good agreement; but Schmidt-Clausen Form Factor gave large errors. PWM is a popular method for controlling the intensity of LEDs and frequencies of around 100Hz, as used in this experiment, are common in marine signal lights. It is evident from the results of observations that the PWM flash profile was the least conspicuous of all the non-rectangular profiles observed. The 50% duty cycle PWM flash profile provided the same conspicuity as a rectangular flash profile with half the peak intensity of the PWM flash profile, which is as expected from the Talbot-Plateau law when the frequency of the modulating waveform is above the flicker fusion frequency[RD18].

For the up triangle flash profiles, MAM Luizov showed good agreement, closely followed by MAM shear q3; Blondel-Rey and Form Factor were further away. Down triangle flash profiles were best represented by MAM shear q3; MAM Luizov, Blondel-Rey and Form Factor were less close. For symmetrical triangles, Form Factor provided a close fit, as did MAM shear q3. Blondel-Rey and MAM Luizov were further away. As with results for this observer at threshold[RD20], there were no significant differences between the up and down triangle plots but the symmetrical triangle plot was slightly enhanced.

Finally, Gaussian flash profiles were best represented by Form Factor or MAM shear q3.

The best overall model for all the flash profiles observed was undoubtedly MAM shear q3 (see Table 1). MAM Luizov, with its unequal treatment of triangular flash profiles was not ideal, being too pessimistic for down triangles, symmetrical triangles and Gaussian flash profiles. Blondel-Rey was pessimistic for all triangles and Gaussian. Form Factor, although good for symmetrical triangles and Gaussian, was optimistic for up and down triangles; for PWM it showed considerable positive errors.

It is interesting to note that the Gaussian flash profile was perceived as equally conspicuous as the triangular flashes, despite having a relative time-integrated intensity of 0.4 when compared to a rectangle of the same duration. The triangular and PWM flashes had a relative time integrated intensity of 0.5. Since time-integrated intensity can be related to energy within the flash, it means the Gaussian flash profile was the most energy efficient of all non-rectangular profiles observed, whilst PWM was the least energy efficient.

Table 1 shows the differences between the results of the various apparent intensity models, all with the visual time constant, a, equal to 0.1 seconds, averaged over all flash durations (0.025s to 1.0s) per profile.

Flash Profile	Blondel-Rey	Form Factor	MAM Luizov	MAM shear q3
Rectangle	-1.9%	-1.9%	-1.9%	-1.6%
PWM	-3.6%	+31.5%	-1.9%	-4.4%
Up Triangle	-15.0%	+9.8%	+1.9%	-5.8%
Down Triangle	-13.8%	+10.8%	-24.4%	-5.3%
Symmetrical Triangle	-26.3%	+0.8%	-20.3%	-7.6%
Gaussian	-23.6%	-0.4%	-17.7%	-6.3%
Average All Profiles	-14.0%	+8.4%	-10.7%	-5.2%
Max All Profiles	-1.9%	+31.5%	+1.9%	-1.6%
Min All Profiles	-26.3%	-1.9%	-24.4%	-7.6%

Table 1 Average Differences between Observed Apparent Intensity Results and Effective Intensity Models

9 Considerations

Frequency of Flash Repetition

There is a variable that affects the threshold perception of a flash of light and that is the frequency at which the flash is repeated. It is known from previous experiments[RD15] that a higher repetition rate of flash presentation increases its conspicuity at threshold. The flashes in this experiment all had an eclipse time of one second. For a 0.025s flash, the repetition frequency was 0.976Hz; for a one second flash, it was 0.5Hz. However, this experiment was carried out at supra-threshold where the effects of frequency have not been validated; therefore, no correction of results has been carried out.

Standard Observer

It is usual for scientific institutions, such as the Commission Internationale de l'Eclairage (CIE) to obtain results from a large number of observers from which an average, or 'standard observer', can be obtained. However, organisations that are concerned with safety, such as aid to navigation providers, are more likely to base their standard on a low percentile performer to ensure that signals can be seen by the majority of observers. Observer I has been identified in previous experiments as having low but consistent apparent intensity performance[RD13].

10 Conclusions

The symmetrical triangle flash profile was slightly more conspicuous than the up or down triangle and Gaussian flash profiles. A similar relationship between these flash profiles was noticed for this observer in a previous experiment at threshold[RD20].

The observer perceived little difference in relative apparent intensity between the up triangle, down triangle and Gaussian flash profiles. This is contrary to the predictions of the MAM Luizov method. It is concluded therefore that MAM, with the Luizov *q(t)* of $a/(a+t)^2$ and a visual time constant, *a*, of 0.1 seconds, although previously recommended for rectangular flash profiles[RD13] [RD14], is not suitable for complex flash profiles above threshold because it predicts a difference in asymmetrical flash profiles that is not borne out by observation.

The shortcomings of the Schmidt-Clausen Form Factor method are highlighted in Table 1 and Figure 8. It is not suitable for PWM flash profiles because it gives large positive errors of more than 30%. For up and down triangle flash profiles, the Form Factor method is also too optimistic by a factor of around 10%.

The Blondel-Rey method is difficult to apply to complex flash profiles and relies upon an iterative technique. This was one reason why the Schmidt-Clausen Form Factor method found favour in some applications. Although it produced acceptable results for rectangular and PWM flash profiles, it was overly pessimistic for symmetrical triangle and Gaussian flashes.

The MAM shear q3 method with a visual time constant, *a*, of 0.1s fits the observer's results for all six flash profiles with acceptable accuracy. All errors were negative when compared with the average of observations for each flash profile, the maximum being -7.6% for the symmetrical triangle flash. The standard error of the results for those ten symmetrical triangle observations varied from 4.7% to 14.5%, depending on flash duration; the average for all flash durations was 7.0%.

11 Recommendations

It is recommended that the Modified Allard Method with a shear q3 *q(t)* (MAM shear q3) and a time constant, *a*, of 0.1 seconds be used for the determination of apparent intensity for all flashes at an observer illuminance of 0.2 microlux, such as those exhibited by marine aid to navigation light signals.

The findings of this report should be presented to CIE Technical Committee TC2-49 and to the IALA Engineering Committee, as it may have an impact on IALA Recommendations[RD12].

The current Modified Allard Method, with its *q(t)* of $a/(a+t)^2$ as suggested by Luizov, is only one way of modifying Allard's original model. If a different *q(t)* is used, should it be called the

'Modified Modified Allard Method' (MMAM)? Perhaps it should be suggested to CIE that the term 'Modified Allard Method' or 'MAM' be used to describe any convolution method with a *q(t)* that is different to the exponential function originally used by Allard. The name of the *q(t)* could be appended in brackets, thereby identifying it; e.g. MAM (Luizov), MAM (shear q3).

Annex 1 Raw Illuminance Values in microlux

Rectangle

Flash Duration (s)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)
0.025	0.18	0.81	0.19	0.88	0.19	0.88	0.19	0.88	0.2	0.8	0.21	0.88	0.21	0.88	0.2	0.88	0.2	0.88	0.2	0.88
0.05	0.18	0.48	0.19	0.56	0.19	0.49	0.19	0.66	0.2	0.42	0.21	0.57	0.21	0.48	0.2	0.52	0.2	0.52	0.2	0.49
0.1	0.17	0.27	0.18	0.32	0.19	0.3	0.19	0.38	0.2	0.31	0.2	0.37	0.2	0.27	0.2	0.35	0.2	0.29	0.2	0.33
0.2	0.18	0.19	0.19	0.25	0.19	0.25	0.19	0.25	0.2	0.23	0.2	0.27	0.2	0.27	0.2	0.26	0.2	0.28	0.2	0.24
0.3	0.18	0.17	0.18	0.19	0.19	0.21	0.19	0.22	0.2	0.22	0.2	0.23	0.2	0.23	0.2	0.24	0.2	0.19	0.2	0.25
0.4	0.18	0.23	0.18	0.22	0.19	0.19	0.19	0.22	0.2	0.19	0.2	0.24	0.2	0.21	0.2	0.21	0.2	0.21	0.2	0.21
0.5	0.18	0.16	0.18	0.24	0.19	0.21	0.19	0.19	0.2	0.19	0.2	0.19	0.2	0.18	0.2	0.23	0.2	0.18	0.2	0.21
0.7	0.18	0.16	0.18	0.19	0.19	0.17	0.19	0.2	0.2	0.18	0.2	0.2	0.2	0.19	0.2	0.2	0.2	0.18	0.2	0.22
1.0	0.18	0.19	0.18	0.17	0.19	0.19	0.19	0.16	0.2	0.19	0.2	0.19	0.2	0.18	0.2	0.19	0.2	0.19	0.2	0.17
Steady	0.18	0.15	0.18	0.17	0.19	0.16	0.19	0.15	0.2	0.17	0.21	0.18	0.2	0.19	0.2	0.17	0.2	0.19	0.2	0.17

PWM

Flash Duration (s)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)
0.05	0.2	0.88	0.19	0.88	0.2	0.88	0.21	0.89	0.2	0.88	0.2	0.86	0.18	0.9	0.18	0.85	0.2	0.9	0.21	0.89
0.1	0.2	0.63	0.19	0.52	0.2	0.56	0.21	0.73	0.19	0.58	0.2	0.52	0.19	0.67	0.2	0.62	0.2	0.58	0.21	0.56
0.2	0.2	0.48	0.19	0.43	Void	Void	0.21	0.42	0.19	0.44	0.2	0.47	0.19	0.54	0.2	0.49	0.2	0.52	0.21	0.53
0.3	0.21	0.44	0.19	0.39	0.2	0.38	0.2	0.41	0.19	0.42	0.2	0.49	0.19	0.63	0.2	0.51	0.2	0.47	0.21	0.49
0.4	0.21	0.42	0.19	0.45	0.2	0.39	0.2	0.37	0.2	0.38	0.2	0.41	0.19	0.51	0.2	0.47	0.2	0.41	0.21	0.48
0.5	0.21	0.49	0.19	0.35	0.2	0.31	0.2	0.36	0.19	0.41	0.2	0.35	0.19	0.42	0.2	0.46	0.2	0.38	0.21	0.44
0.7	0.21	0.46	0.19	0.33	0.2	0.37	0.2	0.39	0.19	0.38	0.2	0.33	0.19	0.47	0.2	0.42	0.2	0.39	0.21	0.42
1.0	0.18	0.48	0.19	0.37	0.2	0.32	0.2	0.34	0.2	0.36	0.2	0.35	0.19	0.43	0.2	0.41	0.2	0.37	0.2	0.4
Steady	0.19	0.18	0.19	0.14	0.2	0.18	0.21	0.15	0.2	0.19	0.2	0.14	0.19	0.15	0.2	0.18	0.2	0.18	0.21	0.18

Up Triangle

Flash Duration (s)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)
0.05	0.2	0.86	0.2	0.87	0.2	0.76	0.2	0.88	0.2	0.83	0.2	0.88	0.18	0.86	0.19	0.89	0.19	0.86	0.19	0.89
0.1	0.19	0.5	0.2	0.51	0.2	0.44	0.2	0.56	0.2	0.51	0.2	0.54	0.18	0.53	0.19	0.55	0.19	0.58	0.19	0.56
0.2	0.2	0.37	0.2	0.35	0.2	0.4	0.2	0.34	0.2	0.32	0.2	0.34	0.18	0.33	0.19	0.41	0.19	0.35	0.19	0.37
0.3	0.2	0.34	0.2	0.32	0.2	0.33	0.2	0.29	0.2	0.33	0.2	0.3	0.18	0.31	0.19	0.34	0.19	0.34	0.19	0.35
0.4	0.2	0.33	0.2	0.27	0.2	0.25	0.2	0.32	0.2	0.29	0.2	0.25	0.18	0.29	0.19	0.36	0.19	0.3	0.19	0.28
0.5	0.21	0.29	0.2	0.26	0.2	0.23	0.2	0.24	0.2	0.26	0.2	0.23	0.18	0.24	0.19	0.3	0.19	0.29	0.19	0.31
0.7	0.21	0.23	0.2	0.24	0.2	0.2	0.2	0.24	0.2	0.24	0.2	0.22	0.19	0.28	0.19	0.33	0.19	0.23	0.19	0.32
1.0	0.21	0.24	0.2	0.2	0.2	0.2	0.2	0.21	0.2	0.18	0.2	0.21	0.19	0.24	0.19	0.26	0.19	0.21	0.19	0.26
Steady	0.21	0.17	0.2	0.2	0.2	0.17	0.2	0.16	0.2	0.18	0.2	0.18	0.18	0.17	0.19	0.18	0.2	0.17	0.19	0.17

Down Triangle

Flash Duration (s)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)
0.05	0.2	0.85	0.21	0.87	0.19	0.84	0.21	0.82	0.21	0.88	0.18	0.88	0.21	0.89	0.21	0.89	0.2	0.89	0.21	0.88
0.1	0.21	0.51	0.21	0.5	0.22	0.53	0.21	0.55	0.21	0.54	0.19	0.74	0.2	0.53	0.21	0.53	0.2	0.48	0.21	0.52
0.2	0.21	0.43	0.21	0.33	0.22	0.39	0.21	0.46	0.21	0.35	0.19	0.43	0.2	0.42	0.21	0.36	0.2	0.4	0.21	0.4
0.3	0.21	0.36	0.21	0.39	0.22	0.36	0.21	0.31	0.21	0.35	0.19	0.36	0.2	0.32	0.21	0.37	0.2	0.31	0.21	0.3
0.4	0.21	0.26	0.21	0.32	0.22	0.3	0.21	0.32	0.21	0.35	0.19	0.34	0.2	0.34	0.21	0.33	0.2	0.35	0.21	0.3
0.5	0.21	0.26	0.21	0.3	0.22	0.33	0.21	0.28	0.21	0.27	0.19	0.32	0.2	0.32	0.21	0.25	0.2	0.26	0.21	0.3
0.7	0.21	0.25	0.21	0.27	0.22	0.29	0.21	0.28	0.21	0.28	0.19	0.25	0.2	0.26	0.21	0.26	0.2	0.25	0.21	0.25
1.0	0.21	0.22	0.21	0.27	0.22	0.26	0.21	0.3	0.21	0.25	0.19	0.23	0.21	0.29	0.21	0.24	0.19	0.2	0.17	0.21
Steady	0.21	0.18	0.21	0.17	0.22	0.17	0.21	0.19	0.21	0.19	0.18	0.17	0.21	0.18	0.21	0.2	0.2	0.19	0.21	0.17

Symmetrical Triangle

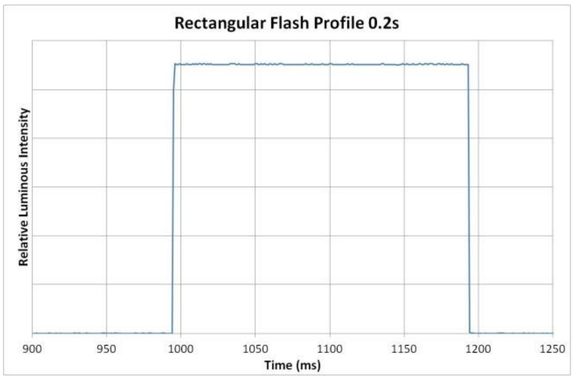
Flash Duration (s)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)
0.05	0.2	0.79	0.21	0.89	0.21	0.78	0.21	0.77	0.21	0.88	0.21	0.89	0.2	0.8	0.2	0.82	0.21	0.76	0.21	0.81
0.1	0.2	0.5	0.21	0.45	0.21	0.44	0.21	0.56	0.21	0.51	0.21	0.52	0.21	0.45	0.2	0.51	0.21	0.5	0.21	0.53
0.2	0.2	0.34	0.21	0.48	0.21	0.35	0.21	0.35	0.21	0.36	0.21	0.33	0.21	0.35	0.2	0.3	0.21	0.32	0.21	0.31
0.3	0.2	0.29	0.21	0.3	0.21	0.31	0.21	0.28	0.21	0.31	0.21	0.27	0.21	0.27	0.2	0.27	0.21	0.31	0.21	0.29
0.4	0.2	0.26	0.21	0.33	0.21	0.26	0.2	0.25	0.21	0.26	0.21	0.28	0.18	0.22	0.2	0.25	0.21	0.25	0.21	0.31
0.5	0.2	0.24	0.21	0.25	0.21	0.27	0.2	0.26	0.21	0.27	0.21	0.29	0.19	0.23	0.2	0.25	0.2	0.23	0.2	0.25
0.7	0.2	0.21	0.21	0.26	0.21	0.24	0.2	0.24	0.21	0.26	0.21	0.24	0.2	0.22	0.2	0.24	0.2	0.21	0.2	0.23
1.0	0.2	0.19	0.21	0.24	0.21	0.23	0.2	0.25	0.21	0.25	0.21	0.22	0.2	0.23	0.2	0.23	0.2	0.2	0.21	0.22
Steady	0.2	0.15	0.21	0.17	0.21	0.19	0.21	0.19	0.21	0.15	0.21	0.19	0.2	0.15	0.2	0.16	0.21	0.18	0.21	0.16

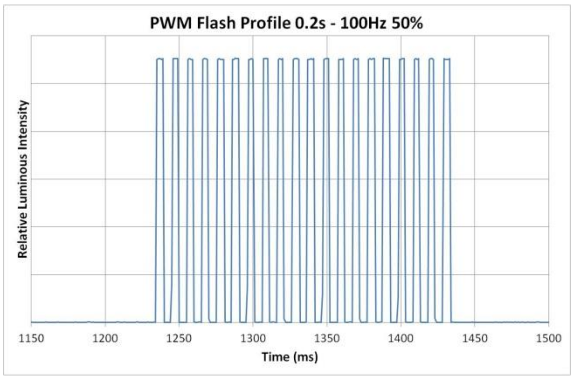
Gaussian

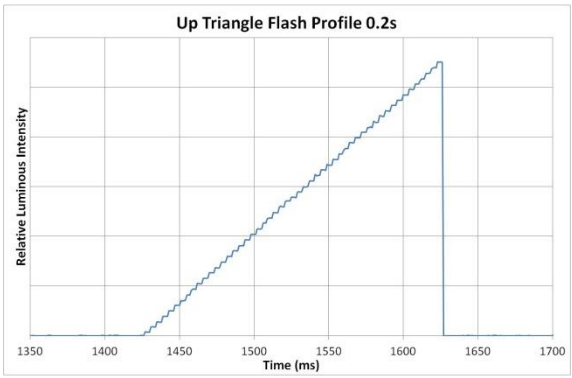
Flash Duration (s)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)	Steady (µlux)	Peak Flash (µlux)
0.05	0.19	0.89	0.2	0.89	0.2	0.89	0.19	0.89	0.19	0.89	0.19	0.89	0.19	0.9	0.2	0.89	0.2	0.89	0.2	0.89
0.1	0.19	0.48	0.19	0.45	0.19	0.58	0.19	0.67	0.19	0.63	0.19	0.63	0.21	0.64	0.2	0.56	0.2	0.64	0.2	0.56
0.2	0.19	0.35	0.19	0.35	0.19	0.34	0.19	0.39	0.19	0.36	0.19	0.39	0.2	0.33	0.21	0.4	0.2	0.44	0.2	0.33
0.3	0.2	0.27	0.19	0.28	0.19	0.28	0.19	0.33	0.19	0.26	0.19	0.3	0.2	0.35	0.21	0.31	0.2	0.33	0.2	0.28
0.4	0.2	0.26	0.19	0.26	0.19	0.23	0.19	0.27	0.19	0.26	0.19	0.32	0.2	0.3	0.21	0.32	0.2	0.27	0.2	0.28
0.5	0.2	0.22	0.19	0.28	0.19	0.27	0.19	0.21	0.19	0.27	0.19	0.26	0.2	0.26	0.21	0.29	0.2	0.28	0.2	0.28
0.7	0.2	0.21	0.19	0.27	0.19	0.22	0.19	0.24	0.19	0.26	0.19	0.27	0.2	0.25	0.21	0.24	0.19	0.25	0.21	0.22
1.0	0.2	0.22	0.19	0.22	0.19	0.19	0.19	0.19	0.2	0.22	0.2	0.21	0.2	0.25	0.21	0.24	0.21	0.25	0.21	0.25
Steady	0.2	0.22	0.19	0.19	0.19	0.16	0.19	0.15	0.19	0.15	0.19	0.17	0.2	0.19	0.21	0.17	0.2	0.18	0.2	0.16

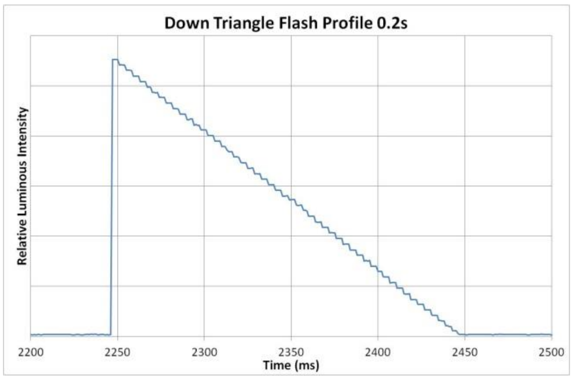
Annex 2 Examples of Flash Profiles Generated

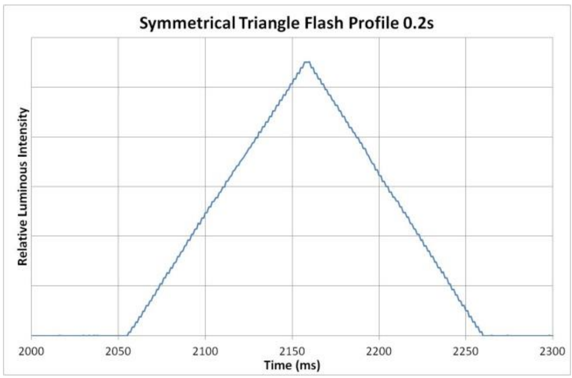
The following flash profiles were measured by a photometer and digitally recorded at 1000 samples per second. The photometer slew rate was around 100 microseconds.

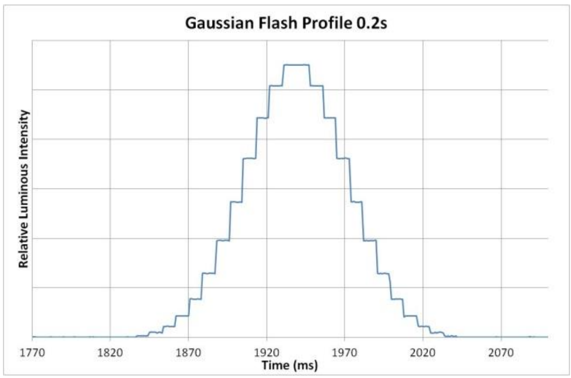












Annex 3 Examples of Impulse Functions (*q(t)s*)

For a convolution, or Allardian, method of determining effective intensity, an impulse function, *q(t)*, is convolved with the flash profile. The peak value of the resultant convolution is taken as the effective or apparent intensity value. Three impulse functions are shown in Figure 9 for a visual time constant, *a*, of 0.1 seconds. Figure 10 shows a graph of the resultant convolution of a rectangular flash profile with the MAM Luizov *q(t)*.

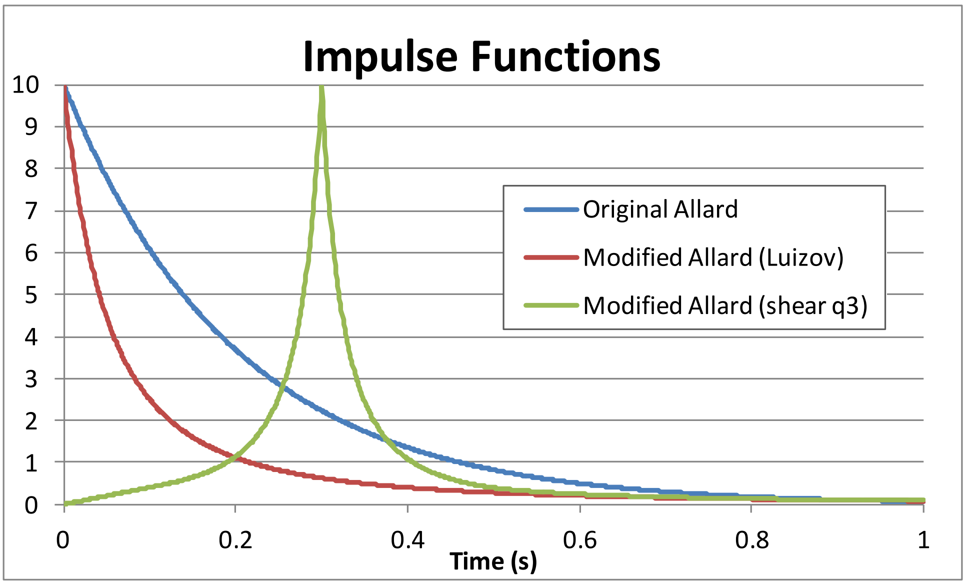


Figure 9 Three impulse functions, where *a* = 0.1s

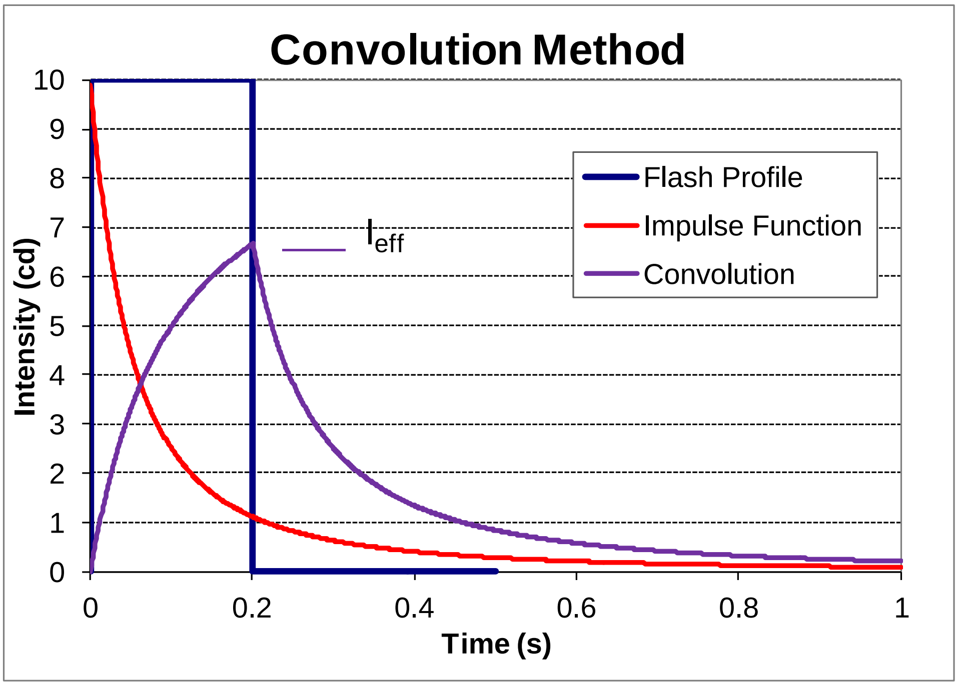


Figure 10 Graph of Convolution Method using a Luizov *q(t)*, where *a* = 0.1s

Annex 4 Brief History of Effective Intensity

How a human perceives a flashing light has been a subject of debate for centuries. In 1885, Bloch proposed a relationship between the duration of a flash of light and its perceived brightness, giving rise to Bloch's law of temporal summation[RD3]. This concept was counter to Allard's [RD1], some nine years earlier, that proposed a convolution of the flash shape with an exponential impulse response function. Blondel and Rey's 1911 proposal[RD4] for the perception of a flash of light, which became a widely used method for evaluating effective intensity over several decades, was based on Bloch's law.

In 1960, Luizov[RD11] proposed using a convolution method, similar to Allard's, but with an impulse response function based on a derivative of the Blondel-Rey formula. This had the advantage that the calculated effective intensity for rectangular flashes agreed with the Blondel-Rey method but that it could be applied to complex flash shapes and repeated flashes; something that proved impractical for other methods except Allard's. The Modified Allard Method[RD16], as Luizov's proposal came to be known, was presented to CIE in 2003 and adopted by IALA in 2008[RD12]. IALA had previously recommended the Schmidt-Clausen Form Factor method [RD17], which was based on Blondel and Rey's method but was simpler to apply. Schmidt-Clausen had also carried out experiments on non-rectangular flash profiles, albeit symmetrical ones. It was the known shortcomings of the Form Factor method in dealing with complex flash shapes and repeated flashes that prompted IALA's decision to adopt the Modified Allard Method.

Although the Modified Allard Method yields the same effective intensity values as the Blondel-Rey and Form Factor methods for rectangular flash shapes, one troubling aspect is that it does not obey Bloch's law. Non-rectangular flash shapes of equal temporal summation may yield quite different effective intensity values when the Modified Allard Method is applied and this is at odds with the widely accepted Blondel-Rey method. Bloch's law certainly holds true for flashes of a short duration but, other than Schmidt-Clausen's experiments [RD17], it has not been tested over a wide range of complex flash shapes or durations. In 1972, Blaise [RD2] suggested an experiment that would prove or disprove Bloch's law, which involved observation of flashes with an asymmetrical triangle shape. Two equal but chirally opposite triangular flash shapes would be observed. If they appeared to be the same brightness to the observer, Bloch's law would be vindicated. If brightnesses appeared unequal, Bloch's law would be disproved.

A threshold experiment carried out in 2015 in Berlin [RD9] on triangular flashes of 0.4 seconds duration showed that, on average, observers perceived little or no difference between chirally opposite triangular flash profiles. A further threshold experiment in November 2015[RD20] showed that three observers perceived little or no difference between chirally opposite triangular flashes of durations between 0.05 seconds and one second. These two experiments, prompted by Blaise's suggestion, proved that Bloch's law was valid at the threshold of perception up to and including flashes one second long, thereby casting doubt on the validity of the Modified Allard Method of determining effective intensity.

Couzin [RD8] showed that the Luizov function, used as the impulse response function for the Modified Allard Method, could be further modified by using a 'shearing' function in order to provide parity for chirally opposite triangular flashes, whilst still maintaining equivalence with Blondel-Rey for rectangular flashes. Results from the further threshold experiment [RD20] showed significant differences between the results of three observers. However, Couzin's 'shear q3' function, used as the impulse response function for the Modified Allard Method, with a visual time constant, *a*, of 0.2 seconds, provided a model that was more in line with average results than other methods.

The term 'effective intensity' is only valid at the threshold of perception. For supra-threshold levels of illuminance, the term 'apparent intensity' has historically been used. When discussing

Toulmin-Smith and Green's results from 1933[RD19], Hampton suggested varying the value of the visual time constant, *a*, linking it to the illuminance value, in order to provide an appropriate apparent intensity model for different supra-threshold levels of illuminance. Results from supra-threshold experiments on rectangular flashes [RD13] [RD14] confirmed this concept. However, for non-rectangular flash profiles at supra-threshold, it may be necessary to vary the visual time constant, *a*, and the impulse response function, depending on the illuminance of the flash of light at the observer. When considering marine aid to navigation lights, the night time luminous range is based upon an observer illuminance of 0.2 microlux, a level above threshold.

When background luminance is present behind the observed flashing light, IALA [RD12] recommend two further levels of illuminance: 2 microlux, for minor background lighting; and 20 microlux for substantial background lighting. Although, using Hampton's model, this would suggest a significant change in the value of the visual time constant, *a*, the effect of a background luminance (against which the flashing light illuminance is contrasted) adds a further variable that needs to be considered.